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A *Chandra* observation of the long-duration X-ray transient KS 1731–260 in quiescence: too cold a neutron star?

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ABSTRACT

After more than a decade of actively accreting at about a tenth of the Eddington critical mass accretion rate, the neutron-star X-ray transient KS 1731–260 returned to quiescence in early 2001. We present a *Chandra*/ACIS-S observation taken several months after this transition. We detected the source at an unabsorbed flux of $\sim 2 \times 10^{-13}$ erg cm^{-2} s^{-1} (0.5–10 keV). For a distance of 7 kpc, this results in a 0.5–10 keV luminosity of $\sim 1 \times 10^{33}$ erg s^{-1} and a bolometric luminosity approximately twice that. This quiescent luminosity is very similar to that of the other quiescent neutron star systems. However, if this luminosity is due to the cooling of the neutron star, this low luminosity may indicate that the source spends at least several hundreds of years in quiescence in between outbursts for the neutron star to cool. If true, then it might be the first such X-ray transient to be identified and a class of hundreds of similar systems may be present in the Galaxy. Alternatively, enhanced neutrino cooling could occur in the core of the neutron star which would cool the star more rapidly. However, in that case the neutron star in KS 1731–260 would be more massive than those in the prototypical neutron star transients (e.g., Aql X-1 or 4U 1608–52).

Subject headings: accretion, accretion disks — stars: individual (KS 1731–260)— X-rays: stars

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1. Introduction

The X-ray transients are a special sub-group of low-mass X-ray binaries (LMXBs). These systems are usually very dim, with X-ray luminosities of 10^{30-34} erg s^{-1}, but they exhibit sporadic outbursts during which the luminosity increases to 10^{36-39} erg s^{-1}. The exact mechanisms for the quiescent X-ray emission are still uncertain (e.g., Menou et al. 1999; Campana & Stella 2000; Bildsten & Rutledge 2001). The most promising and testable model for the quiescent properties of neutron star transients is the one which assumes that the X-rays below a few keV[5] are due to cooling of the neutron star after the accretion has stopped (van Paradijs et al. 1987; Verbunt et al. 1994; Asai et al. 1996; Brown, Bildsten, & Rutledge 1998). The main argument against this interpretation used to be that the temperature obtained from black-body fits to the spectral data resulted in very small (<3 km) emitting radii, significantly smaller than the theoretical predictions for neutron star radii. However, recently it has been put forward that black-body fits to the spectra overestimated the effective temperatures and thus underestimated the emitting areas (Brown et al. 1998). The spectra are better and more realistically described by thermal emission from a pure hydrogen atmosphere. By using data of quiescent neutron star systems, Rutledge et al. (1999, 2000) demonstrated that their spectra could indeed be fitted with such hydrogen atmosphere models and emission radii of $\sim$10 km were obtained.

If the quiescent emission below a few keV is indeed due to the cooling of the neutron star, then the actual luminosity is predicted to depend on the time-averaged accretion rate (Brown et al. 1998). Using their cooling model, a distance independent prediction of the expected quiescent flux can be derived of $F_{\rm q} \approx \langle F \rangle/130$ (see also Rutledge et al. 2001b) with $\langle F \rangle$ the time averaged flux of the source. The latter can be rewritten as $\langle F \rangle = t_{\rm o} \langle F_{\rm o} \rangle/(t_{\rm o}+t_{\rm q})$ resulting in $F_{\rm q} \approx \frac{t_{\rm o}}{t_{\rm o}+t_{\rm q}} \times \frac{\langle F_{\rm o} \rangle}{130}$, with $\langle F_{\rm o} \rangle$ the average flux during outburst, $t_{\rm o}$ the average time the source is in outburst, and $t_{\rm q}$ the average time the source is in quiescence. This model indeed appears to reproduce the observed quiescent luminosities (e.g., Rutledge et al. 1999, 2000). Furthermore, Brown et al. (1998) also predicted the very low luminosity of SAX J1808.4–3658 in quiescence (Dotani, Asai, & Wijnands 2000; Wijnands et al. 2001a) due to its very low time averaged accretion rate. Despite these successes, more quiescent systems should be observed to test and refine the model further.

A class of sources not yet compared in this model is that of the long-duration transients (e.g., MXB 1659–298; EXO 0748–676; KS 1731–260 [see below]). These are systems which

[5] In the spectra of several systems, a power law component above a few keV is present (e.g., Asai et al. 1996, 1998) which is not understood but which may be due to residual accretion (see Campana & Stella 2000 for a discussion). Here, we will not discuss this component.

suddenly, like ordinary transients, become X-ray bright but in contrast to the ordinary, short-duration ones, do not disappear after a few weeks to months, but remain active for several years to decades. If the only difference between those systems and the ordinary ones is the duration t_o of the outburst episodes, and everything else is similar, in particular if the time t_q the sources spend in quiescence is similar to that of normal transients, then the neutron stars of such long-duration transients are predicted to be heated to considerably higher temperatures than those in the ordinary ones. Up to recently, this prediction could not be tested because none of the known long-duration neutron star transients which are currently active had turned off. In this *Letter*, we discuss the first results obtained of such a system, KS 1731–260, which turned off in early 2001 after having accreted for over a decade.

KS 1731–260 was discovered in Aug. 1989 using the *Mir*/Kvant instrument and was also found to be active in Oct. 1988 (Sunyaev 1989). The compact object in this transient is a neutron star as it exhibits type-I X-ray bursts (Sunyaev 1989; Sunyaev et al. 1990). Since its initial discovery, its has been observed as a persistent source with *Ginga*, *Sigma*, *ROSAT*, *RXTE*, and *ASCA* (Yamauchi & Koyama 1990; Barret et al. 1992, 1998; Smith et al. 1997; Muno et al. 2000; Narita et al. 2001). Recently, the source became undetectable during the monitoring observations with the All Sky Monitor (ASM) aboard *RXTE*. In Figure 1, the ASM light curve of KS 1731–260 is presented, which shows that in early 2001, after a short period during which solar constraints inhibited monitoring, the source could not be detected anymore near day 1800. Its disappearance was confirmed by its non-detection using pointed *RXTE* observations with the proportional counter array (PCA) and the bulge scan observations of the Galactic center region (Fig. 1; Markwardt 2000; Markwardt et al. 2000), which include KS 1731–260. The first non-detection in the bulge scans was on 2001 Feb. 7. The 1 σ upper limit is 1.7×10^{-11} erg cm^{-2} s^{-1} (2–10 keV; absorbed).

Before it disappeared, KS 1731–260 had been accreting for about 12.5 years. This is the only outburst observed for this source and previous outbursts could have been significantly shorter (less than a year) or considerably longer (several decades). However, if the behavior displayed by KS 1731–260 during its last outburst is typical, then its average outburst duration is of the order of a decade (we use $t_o = 12.5$ years in the following). To estimate its quiescent flux using the Brown et al. (1998) model, its time averaged outburst flux needs to be known. During all outburst observations, the absorbed source fluxes were in the range of 10^{-9}–10^{-8} erg cm^{-2} s^{-1}. The average absorbed flux obtained during the bulge scans from 05 Feb 1999 to 30 Oct 2000 was $\sim 1.7 \times 10^{-9}$ erg cm^{-2} s^{-1} (2–10 keV; with a range of 0.1–4.8 $\times 10^{-9}$ erg cm^{-2} s^{-1}). Due to the limited energy ranges for which those fluxes are quoted and the high column density towards the source, the total unabsorbed fluxes are likely to be in the range of 0.5–1 $\times 10^{-8}$ erg cm^{-2} s^{-1}, or even higher. To obtain a lower limit on the average quiescent time of KS 1731–260, we will assume that its time averaged outburst flux

did not exceed $\sim 10^{-9}$ erg cm^{-2} s^{-1}. It is conceivable that during previous outbursts the source has reached similar flux levels (recurrent transients tend to have similar peak fluxes), so we take as $\langle F_{\rm o} \rangle = 10^{-9}$ erg cm^{-2} s^{-1}. We use this conservative flux to demonstrate later on that even for such a low flux level, the quiescent time of KS 1731–260 might be several hundreds of years. Using the Brown et al. (1998) model, this results in predicted quiescent fluxes of 7.1, 4.3, and 0.85 $\times 10^{-12}$ erg cm^{-2} s^{-1}, for a $t_{\rm q}$ of 1, 10, and 100 years, respectively (see Chen, Shrader, & Livio 1997 for typical observed quiescent times and Lasota 2001 for theoretical expected ones).

2. Observation, analysis, and results

We obtained a *Chandra*/ACIS-S observation on KS 1731–260 on 27 March 2001 00:17–06:23 UTC (only a few months after it turned off; Fig. 1) for a total on-source time of $\sim$20 ksec. During our observation the ACIS-S3 backside-illuminated CCD was used with a 1/4 sub-array. This configuration was chosen to reduce the pile-up problems which would arise if the source were to exceed a luminosity of 10^{34} erg s^{-1} ($\sim 10^{-12}$ erg cm^{-2} s^{-1}). No episodes of high background occurred, so all the data were used. We used the CIAO tools (version 2.1.3) and the threads listed at http://asc.harvard.edu to analyze the data. Two point sources were detected using the tool *celldetect*; one of them is located near the center of the *ROSAT*/HRI error circle of KS 1731–260 (Barret et al. 1998) and can almost certainly be identified with KS 1731–260. For a discussion of its X-ray position (including the identification of the extra source with a star in the 2MASS catalog) and its likely optical/infra-red counterpart, we refer to Wijnands et al. (2001b) and Groot et al. (2001).

The source spectrum was extracted using a circle of 10 pixels in radius on the source position. The background data were obtained by using four background regions, each consisting of a circle with a radius of 10 pixels. The data were rebinned using the FTOOLS routine *grppha* into bins with a minimum of 10 counts per bin. The spectrum was fitted using XSPEC version 11 (Arnaud 1996). We used several models to fit the data and either the column density, $N_{\rm H}$, was fixed to the value obtained by *ROSAT* and *ASCA* (1.1×10^{22} cm^{-2}; Barret et al. 1998; Narita et al. 2001) or it was included in the fit as a free parameter. A pure power-law and a black-body model fit the data equally well, although a power-law model gave a very high photon index of 4 ($N_{\rm H}$ fixed) or 5.3 ($N_{\rm H}$ left free; the resulting value was $\sim 1.7 \times 10^{22}$ cm^{-2}). This strongly suggests that the X-ray spectrum is more likely to be black-body like. Therefore, we concentrate on the black-body fits in the rest of our paper.

The obtained spectral results are listed in Table 1 and the spectrum is shown in Figure 2. Because several quiescent neutron star systems have shown evidence for an extra power-law

component above a few keV in their quiescent spectra (e.g, Asai et al. 1996, 1998), we also fitted the data with a black-body plus power-law model (using a fixed photon index of 1; e.g., Rutledge et al. 2001a). When the column densities are left as a free parameter, its value is consistent with that obtained from the *ROSAT* and *ASCA* data of KS 1731–260. The temperature, kT, of the black body we measure with *Chandra*, is in all cases consistent with 0.3 keV. The unabsorbed 0.5–10 keV black body fluxes are around 1.7×10^{-13} erg cm^{-2} s^{-1}, although the flux is slightly lower when only a black body model was used with a free floating column density. The power-law component flux would be $\sim$ 15% of the total flux in the 0.5–10 keV energy range, but it is not statistically required.

The black body flux results in a 0.5–10 keV luminosity of $\sim 1 \times 10^{33}$ erg s^{-1} (for 7 kpc; Muno et al. 2000). Rutledge et al. (2000) found that the bolometric luminosity of quiescent neutron star systems (using hydrogen atmosphere models) is about a factor of 2 higher than the luminosity in the 0.5–10 keV range (e.g., 4U 1608–52 has a very similar column density and black body temperature in quiescence [Rutledge et al. 1999] and it has only a factor of two higher bolometric luminosity compared to the black-body 0.5–10 keV luminosity; Rutledge et al. 2000). Therefore, we will adopt a bolometric value of $\sim 2 \times 10^{33}$ erg s^{-1} in the rest of this paper, resulting in a quiescent bolometric flux of $\sim 4 \times 10^{-13}$ erg cm^{-2} s^{-1}.

3. Discussion

After actively accreting for 12.5 years, the neutron star X-ray binary KS 1731–260 suddenly turned off in early 2001. It has a quite different outburst behavior than ordinary transients. In those ordinary systems, it is believed (e.g., Lasota 2001 and references therein), that during their quiescent episodes their accretion disks slowly fill due to low-level mass transfer from the companion star via Roche-lobe overflow. During outbursts, this matter is dumped onto the compact object at a rate faster than can be supplied by the donor star and the disk quickly empties. It will slowly refill again in quiescence. However, for KS 1731–260 and similar systems, the mass transfer rate of the companion star can keep up with the mass transfer rate onto the compact object for a considerable time period (12.5 years for KS 1731–260) and the sources become quasi-persistent with quasi-stable accretion disks. It is unclear if and how such sources can be accounted for in the latest versions of the disk instability models to explain the outbursts in X-ray transients (e.g., Lasota 2001).

We have observed KS 1731–260 in quiescence with *Chandra* only a few months after its transition in order to test the cooling neutron star model (see Wijnands 2001 for a short discussion about other models). The bolometric flux of KS 1731–260 in quiescence is

$\sim 4 \times 10^{-13}$ erg cm^{-2} s^{-1}, resulting in a bolometric luminosity of $\sim 2 \times 10^{33}$ erg s^{-1} (for a distance of 7 kpc; Muno et al. 2000). This bolometric luminosity and the black body temperature ($kT \sim 0.3$ keV) are very similar to what has been observed for other, short-duration transients (see, e.g., Asai et al. 1996, 1998; Rutledge et al. 2001a, 2001b). This result is unexpected, because, as explained in Section 1, the long accreting episode should have heated the neutron star in KS 1731–260 to a higher temperature (and thus higher luminosity) than what we have observed. However, this assumes that (i) the Brown et al. (1998) model for short duration transients also applies to systems such as KS 1731–260, (ii) standard cooling operates in the neutron star in KS 1731–260, and (iii) the source spends a similar amount of time in quiescence as the other known X-ray transients.

Therefore, one obvious solution to this discrepancy would be that the time KS 1731–260 spends in quiescence is extremely long compared to other systems. Our general believe on how long transients can be quiescent is based on those systems for which multiple outbursts have been observed and is therefore biased to short quiescent episodes (years to a few decades, basically the time since the birth of X-ray astronomy). For certain types of transients, the quiescent episodes could last significantly longer. However, if the standard cooling model for neutron stars applies here, KS 1731–260 has to be quiescent in between outbursts for at least 200 years. The quiescent intervals most likely have to be considerably longer. To calculate the expected quiescent flux, we used a very conservative bolometric outburst flux of 10^{-9} erg cm^{-2} s^{-1}, but the true value is more likely in the range of $0.5 - 1 \times 10^{-8}$ erg cm^{-2} s^{-1}, or even larger. If indeed this is a typical outburst flux level, this would indicate that the source has to spend over a thousand years in quiescence. In the present day disk instability models (e.g., Lasota 2001; Dubus, Hameury, & Lasota 2001), it is not easy to see how such long quiescent episodes can occur because the accretion disk will slowly fill again, but at a certain point, even small fluctuations in the mass transfer rate from the companion star will trigger an outburst (see, e.g., Lasota 2001 for a discussion). An alternative model for this source might be the companion star instability model.

But if some LMXBs can indeed be quiescent for over a thousand years, then there may be a considerable number of such systems in our Galaxy. Only a rough number estimate can be obtained by assuming that such systems are active on average for ten years and quiescent for thousand years. At the moment, we know of only a few sources which fall in the class of the long-duration transients and which where actively accreting during the last decade (e.g., KS 1731–260, MXB 1659–29, EXO 0748–676, GS 1826–238). Thus, if these assumptions are correct, one would expect not more than several hundred of such systems. Although the numbers are highly uncertain, if indeed such a large number of extra previously unrecognized LMXBs are present in our Galaxy, then they might help to bring the birth rate of binary millisecond radio pulsars and of LMXBs in better agreement (Kulkarni & Narayan 1988;

Coté & Pylyser 1989; see Lorimer 1999 for a recent discussion).

Alternatively, instead of postulating that the quiescent episodes of KS 1731–260 are extremely long, one could also speculate on the possibility that enhanced cooling takes place in the core of the neutron star in this system. If strong enhanced neutrino cooling occurs in the core (Colpi et al. 2001; Ushomirsky & Rutledge 2001), this might cool down the star in a much shorter time span and this could possibly explain why KS 1731–260 is so underluminous in quiescence compared to the expected value inferred from cooling neutron star models (Brown et al. 1998). Colpi et al. (2001) suggested that such a mechanism is at work in the neutron star transient Cen X-4, to explain its low ratio of quiescent to outburst luminosity. They also suggested that this enhanced cooling might be caused by a more massive neutron star in Cen X-4 compared to those in the other systems, which would suggest that a massive neutron star might also be present in KS 1731–260.

Finally, we have assumed that the cooling neutron star model developed by Brown et al. (1998) for the short duration transients, is valid also for the long-duration transients such as KS 1731–260. However, this model might break down for systems like KS 1731–260. It is unclear what the effects of such a long active period are on the crust and the core of the neutron star. It is plausible that the crust looks more like that of a neutron star in a persistent X-ray binary. The X-ray flux observed from KS 1731–260 might be dominated by the state of the crust. However, the core should then be even cooler than we have assumed, which would strengthen our conclusion that KS 1731–260 has to be in quiescence for a very long time. More detailed modeling of the behavior of the neutron star (its crust and its core) needs to be performed to understand long-duration systems like KS 1731–260.

Note added in manuscript We became aware of the work of Burderi et al. (2001) and Rutledge et al. (2001c), using *BeppoSAX* and our *Chandra* quiescent observations of KS 1731–260, respectively. Both papers confirm our conclusion: if the X-ray emission originates from the neutron star surface, KS 1731–260 has to have been in quiescence for $>$1000 years.

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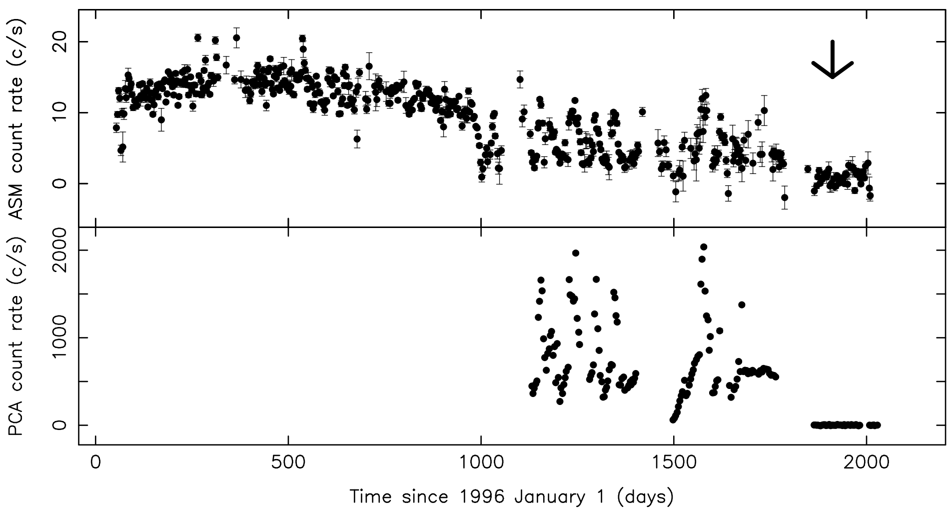

Fig. 1.— The *RXTE*/ASM 1.5–12 keV (top) and the *RXTE*/PCA (bottom) 2–60 keV count rate curves of KS 1731–260. The day the *Chandra* observation was performed is marked with an arrow.

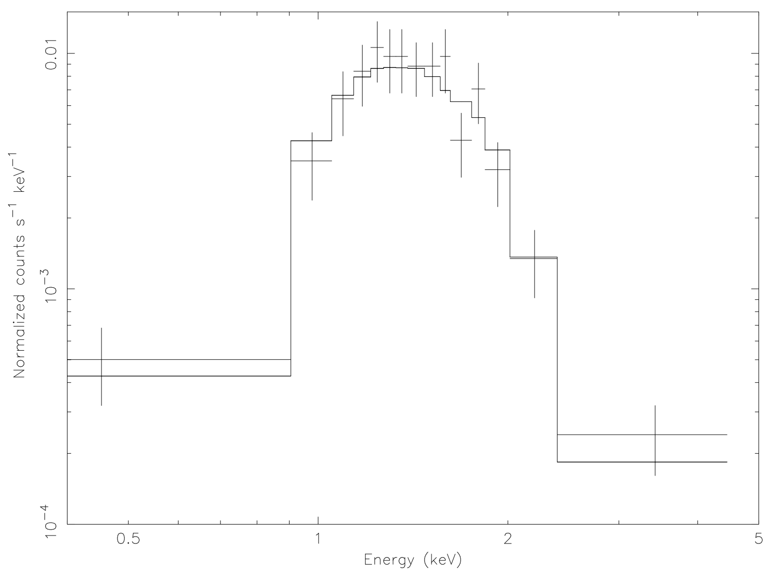

Fig. 2.— The *Chandra*/ACIS-S S3 spectrum of KS 1731–260. The solid line is the best black body fit through the data.

Table 1. Spectral results[a]

Black body		
$N_{\rm H}$ (10^{22} cm^{-2})	$0.9^{+0.4}_{-0.2}$	1.1 (fixed)
kT (keV)	$0.30^{+0.05}_{-0.06}$	0.27 ± 0.03
Norm. (10^{-6})	$1.7^{+2.1}_{-1.7}$	$2.5^{+0.7}_{-0.5}$
F (10^{-13} erg cm^{-2} s^{-1})	1.2	1.7
χ^2/dof	8.0/13	9.0/14
Black body + power law[b]		
$N_{\rm H}$ (10^{22} cm^{-2})	1.1 ± 0.4	1.1 (fixed)
kT (keV)	0.25 ± 0.06	0.25 ± 0.03
Norm. black body (10^{-6})	$2.8^{+8.4}_{-1.7}$	$2.7^{+0.6}_{-0.5}$
Norm. power law (10^{-6})	$2.3^{+1.5}_{-2.0}$	$1.9^{+1.4}_{1.5}$
$F_{\rm tot}$ (10^{-13} erg cm^{-2} s^{-1})	2.0	2.1
$F_{\rm bb}$ (10^{-13} erg cm^{-2} s^{-1})	1.7	1.8
$F_{\rm pl}$ (10^{-13} erg cm^{-2} s^{-1})	0.3	0.3
χ^2/dof	5.6/12	4.9/13

[a]The error bars are for 90% confidence levels. The fluxes are unabsorbed and for 0.5–10 keV

[b]The power law photon index was fixed to 1